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14Titanium alloys are used extensively in aerospace applications mainly due to their superior strength to weight ratio. Different grades of titanium alloys are used for different applications. The alloy Ti-3Al-2.5V is used to make seamless tubes, used in hydraulic systems of aircrafts for its excellent cold formability. Welding of these tubes with other components is indispensable for installing hydraulic systems. Normally fusion welding process, namely Gas Tungsten Arc Welding Process (GTAW) is undertaken to join theses components. Different sized tubes are required to be welded with different end fittings. Production of high quality welds in titanium alloys requires meticulous pre-weld surface preparation of the work-pieces. Conventionally such preparation procedures are chemically based, where the entire component is cleaned by chemical etching in toxic chemicals like hydrofluoric acid, nitric acid etc. This process removes some material from the surface along with the contaminant, exposing fresh material for joining purpose. This method is presently adopted by NAVAIR to clean the tubes prior to welding. However these chemicals are hazardous and environmentally malign. . Handling of these chemicals, disposal and safety of individuals is also of concern. The footprint of these cleaning systems is also too large. The main objective of this project is to develop an environmentally friendly compact titanium alloy tube laser cleaning and welding system for NAVAIR use.

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FINAL PROJECT REPORT

Rapid Repairs: Surface Preparation of Ti-3Al-2.5V alloy tubes by fiber laser and welding

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1) Project Objective:

Titanium alloys are used extensively in aerospace applications mainly due to their superior strength to weight ratio. Different grades of titanium alloys are used for different applications. The alloy Ti-3Al-2.5V is used to make seamless tubes, used in hydraulic systems of aircrafts for its excellent cold formability. Welding of these tubes with other components is indispensable for installing hydraulic systems. Normally fusion welding process, namely Gas Tungsten Arc Welding Process (GTAW) is undertaken to join theses components. Different sized tubes are required to be welded with different end fittings. Production of high quality welds in titanium alloys requires meticulous pre-weld surface preparation of the work-pieces. Conventionally such preparation procedures are chemically based, where the entire component is cleaned by chemical etching in toxic chemicals like hydrofluoric acid, nitric acid etc. This process removes some material from the surface along with the contaminant, exposing fresh material for joining purpose. This method is presently adopted by NAVAIR to clean the tubes prior to welding. However these chemicals are hazardous and environmentally malign. Handling of these chemicals, disposal and safety of individuals is also of concern. The footprint of these cleaning systems is also too large.

The main objective of this project is to develop an environmentally friendly compact titanium alloy tube laser cleaning and welding system for NAVAIR use.

Laser's are being recognized as attractive cleaning tool in many fields, for example semiconductor industry [1,2], nuclear industry [3-7] and in art restoration work [8,9], for its non- contact dry nature of cleaning and its ability to remove selectively a controlled volume of material without damaging the property of the bulk. Several physical mechanisms are involved in laser cleaning process, depending on the material's properties and laser parameters. We have investigated the laser cleaning process in detail and carried out necessary welding trials to ensure the feasibility of laser surface preparation. The details of which will be discussed subsequently.

2) Work carried out under this project

The experimental work carried out under this project is divided in three segments.

i) Edge preparation of Ti alloy tubes.

ii) Laser cleaning of edge prepared tubes.

iii) Welding of laser cleaned tubes with end fittings by Pulsed Gas Tungsten Arc Welding (PGTAW) technique in an orbital welding machine.

2.1) Edge preparation of Ti alloy tubes.

Before carrying out cleaning and welding operation, the edge of the Ti alloy tubes needs to be faced to obtain a perfect joint during welding. A perfect joint is necessary to obtain a sound weld. Figure 1 shows the schematic of the half cross section of the weld joint. Any gap between the abutting surfaces between the tube and the fitting may result in a defective weld. Presence of excessive chamfering reduces the effective wall thickness of the tube at the joint, whereas presence of burrs on the tube edge leaves a gap between the abutting surfaces. If welding is carried out in these conditions, it may lead to a defective weld.

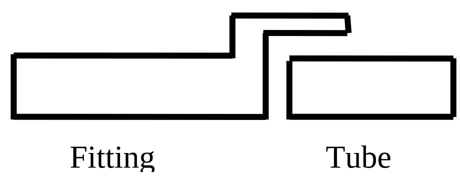


Fig 1: Schematic of the cross section of the weld joint

In this process following points are taken care of.

a) Perpendicularity of the tube axis and the tube face.

b) No chamfering on the tube edge.

c) No burr on the tube surface (inside or outside).

This edge preparation process exposes fresh material of the tube wall for welding.

A portable tube facing machine (M/S Wachas) is being used by us for this purpose. In this machine the tube is held by a grip and the tool is rotated by a motor. Rotational speed of the motor and forward motion of the tool is controlled manually. For limited depth of cutting this machine gives a burr free cut.

2.1) Laser Cleaning of edge prepared tubes

2.2.1) Experimental

The Ti-3Al-2.5V tubes used in this experiment are 9.5 mm in diameter with nominal wall thickness of 0.830 mm. Due to the high affinity of titanium alloys to atmospheric gases at high temperature, the tubes are processed inside a stainless steel chamber (100 mm x 100 mm x 100 mm), which is purged with industrial argon gas and maintains a continuous flow of 2 - 3 liters per minute (lpm) throughout the cleaning process. The schematic of the cleaning system is shown in figure 2.

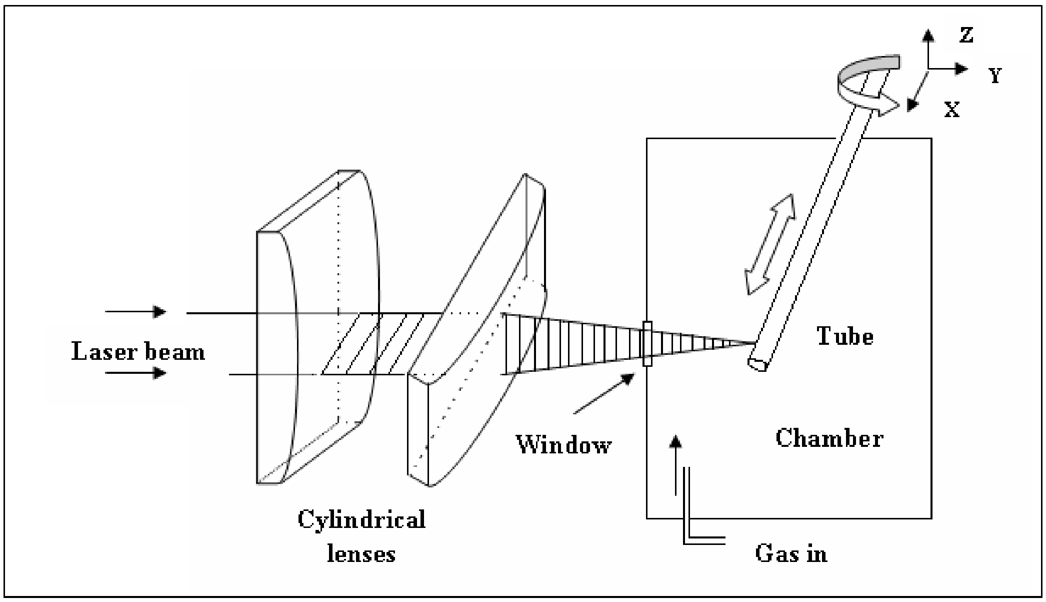


Figure 2 : Schematic of the fiber laser cleaning system (source: A. Kumar).

In this scheme the laser beam is kept stationary and the tube is rotated and moved across the beam to scan the necessary area. Unlike chemical methods, cleaning is done only near the edge of the tube, which gets fused during welding. The beam from a fiber laser (IPG: YLP-RA-1/50/30/30) is incident on the tube through a quartz window mounted on the chamber. The beam incident angle is kept around 45^0 with the normal to the tube, so that the beam can be easily focused on the inner surface of the tube without any hindrance. The tube is mounted on a motorized rotational stage (Newport: SR50PP) and is positioned inside the chamber through an opening provided on the flange of the chamber. The rotational stage in turn, is mounted on an X-Y-Z translational stage (Newport: MFACC). Movement in X axis provides the required linear scan along the length of the tube. The tube surface is brought under the focused beam by moving the Y translational stage. Vertical positioning of the tube with respect to the incoming beam is achieved by controlling the Z axis. Once, a tube is positioned perfectly with respect to the focused beam, the X axis and the rotational stage is required to be operated for scanning. A programmable motion controller (Newport: ESP 300) is used to control the X translational and rotational motion of the tube. The entire setup with the laser, focusing optics and the cleaning chamber is suitably enclosed to reduce reflected and scattered radiation during processing in the working place. We have scanned the surface of the tube across a rectangular focused beam, in order to obtain better efficiency of cleaning [13]. A rectangular focal spot is obtained by using cylindrical lenses. Combination of two cylindrical lenses (focal length: 100 mm) is used as shown in figure 1, to vary the focal spot size on the tube by varying the distance between them. Initially the outer surface of the tube is cleaned. The tube is scanned across the beam in the following manner (figure 2). The scan starts from the edge of the tube (position 1). Linear motion in the X direction (axial) brings the laser spot to position 2. Now rotation of the tube brings the spot to position 3. Again, a linear scan in the opposite direction brings the spot to position 4. A further rotation of the tube brings the spot to position 5. The axial scanning is restricted to 2 mm from the edge of the tube co scanning continues for a full rotation (360^0) of the tube.

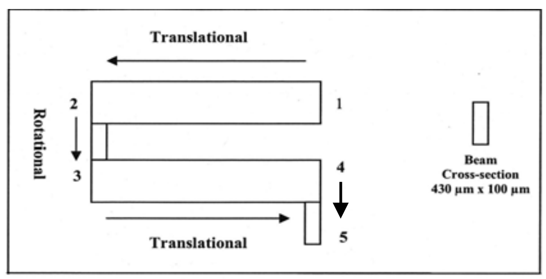


Figure 3: Schematic of the scanning sequence

In figure 3, movement of the beam spot is shown, the tube actually moves in the opposite direction. For clarity the overlap between successive cleaned areas is not shown in the figure. Throughout the experiment the velocities of the motorized X axis translational stage and rotational stage have been kept at their maximum specified values to reduce the cleaning time. The velocity of linear motion and rotational motion has been kept at 2.5 mm/s and 4 deg/s respectively. The angle of rotation followed after each translational motion is chosen to provide at least 30 - 40 % overlap with successive scanned area. It has been observed, for an optimum beam size of 430 µm x 100 µm, a rotation of 2.75 -

3.00 degrees provides the required overlap. After cleaning the outer surface, the Y stage is moved to bring the inner surface at the laser focus. The relative position of the tube

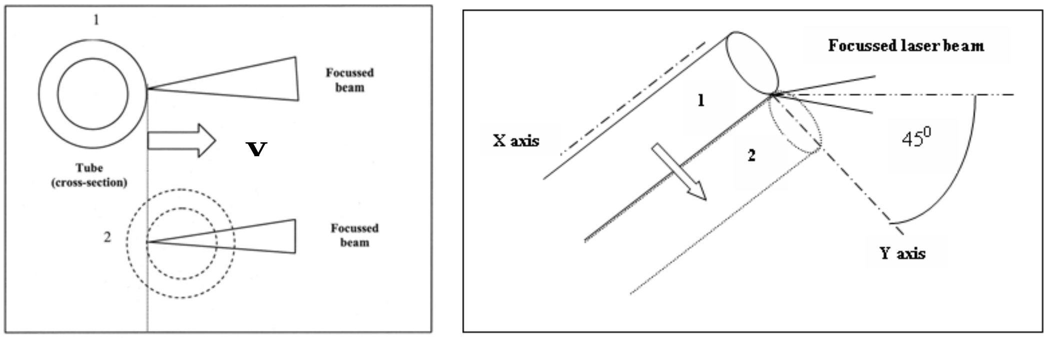


Figure 4 : Relative position of the tube surfaces wrt the focused beam during laser cleaning, position 1 – during outer surface cleaning, position 2 – during inner surface cleaning. (a) Side view, (b) isometric view.(source: A. Kumar)

with respect to the laser beam while cleaning outer and inner surfaces is shown in figures 4a and 4b. The inner surface is cleaned in the same way as is done for the outer surface. Figure 5 shows few laser cleaned tube inner and outer edges.

Experiments have been performed with different laser fluences at different repetition rates to obtain the cleaning and damage threshold parameters. Cleaned surface has been evaluated by optical microscopy, profilometry, SEM, EDX and XPS.

Figure 5 : Photograph of laser cleaned tube inner and outer edges.

2.2.2) Results.

Titanium is a highly active material and readily oxidizes in atmosphere. When fresh titanium material is exposed to ambient atmosphere, a passive oxide film is spontaneously formed on its surface. The characteristics of the oxide film depend on chemical composition, structure, morphology and mechanical condition of the material and other conditions like temperature, oxygen partial pressure etc. [14]. In order to obtain a sound weld with these alloys, the oxide layer and the residual contaminants present on the tube surface needs to be removed thoroughly. Figure 6 shows a SEM image indicating presence of the oxide layer on the tube surface. The laser cleaning threshold and material damage threshold parameters have been evaluated visually and by optical microscopy.

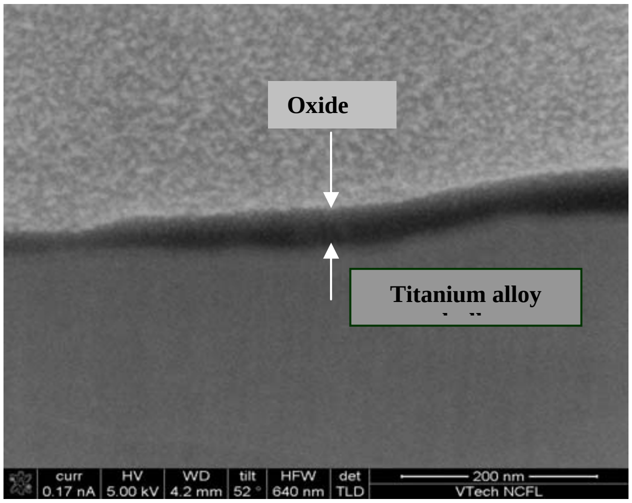
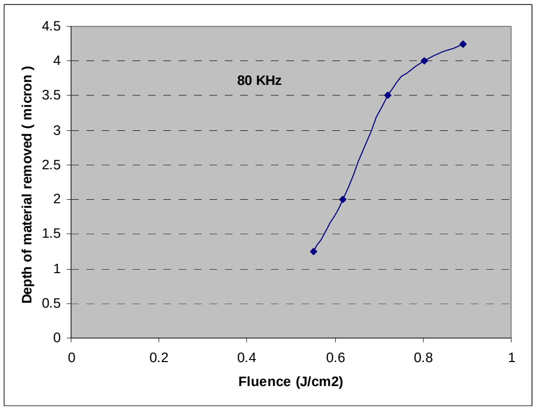


Figure 6 : SEM image of the tube surface showing the presence of thin oxide layer.

Laser cleaning experiments have been performed at repetition rates from 30 kHz to 80 kHz with different laser fluences keeping linear and rotational scanning speed constant. The laser fluence has been varied systematically aiming to find the optimum condition for the removal of the oxide layer without damaging the bulk. Figure 7 a and 7 b shows the variation in depth of material removal with different fluences at 80 kHz and 30 kHz respectively. Figure 6a shows that the threshold fluence for obtaining cleaning at 80 kHz



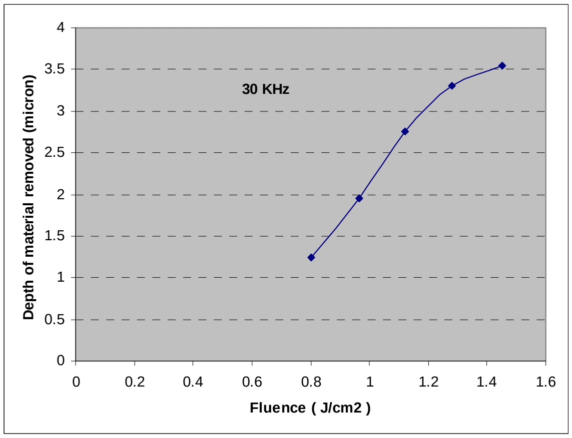


Figure 7: Variation of depth of material removed as function of laser fluence.
(a) repetition rate : 80 kHz, (b) repetition rate : 30 kHz.

is ~ 0.55 J/cm^2. Irradiation with fluence slightly less than 0.55 J/cm^2 shows some visual evidence of surface perturbation but does not remove the oxide layer from the surface. Increasing the laser fluence above the threshold value, results in removal of the oxide layer, which is evident from the shiny bright silvery appearance of the cleaned area. Figure 6 b shows that at 30 kHz, the threshold fluence for cleaning needs to be increased to ~ 0.8 J/cm^2. As the number of interacting pulses decreases at this repetition rate, operating at lower fluence does not yield any cleaning. At 30 kHz, increasing the fluence only, results in satisfactory cleaning. With further increase in fluence, the depth of material removal increases almost linearly initially, later reduces to a lower rate and tends to get saturated. The absorption of incoming photons by the laser produced plasma at higher fluences may be responsible for this reduction. It is observed that a fairly large window of parameters exists for cleaning the tubes. Threshold fluence, at any other repetition rate between 30 kHz and 80 kHz is found to be between 0.55 J/cm^2 and 0.8 J/cm^2. It has been found that, laser fluence above 1.75 J/cm^2 results in damage of the surface by forming pits. The depth of removed material is determined by measuring the diameter of the tube before and after cleaning with the help of a high precision micrometer. Surface profilometry has also been carried out to find out the same. Figure 8 shows the surface profile of the cleaned area. At optimum laser cleaning parameters (repetition rate: 80 kHz and fluence ~ 0.64 J/cm^2) approximately 2 micron of material is removed from the surface. A cleaning rate of ~ 10 mm^2 / minute has been achieved.

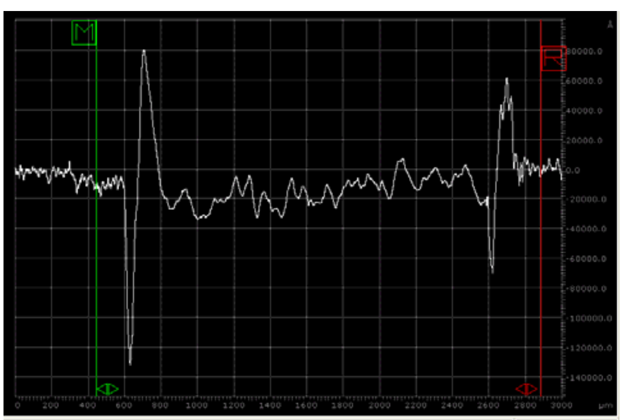


Figure 8 : Photograph of the surface profilometry of the cleaned area. X axis: One box – 200 μm, Y axis: One box – 2 μm

Figure 9 shows the SEM picture of the as received and the laser cleaned surface. The

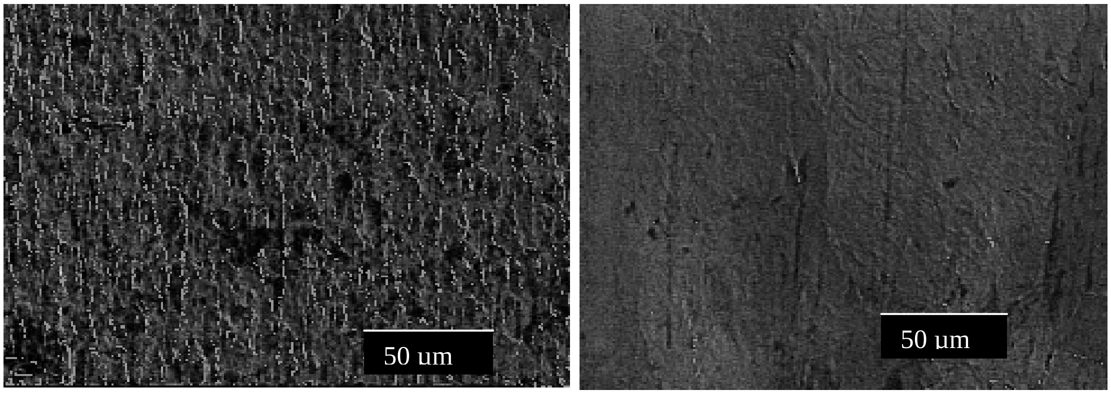


Figure 9 : SEM image of (a) as received and (b) laser cleaned tube surface

cleaned area visually can be easily recognized by its shining silvery appearance. It is also seen that laser cleaning provides a smooth processed surface. The cleaned and as received surfaces have also been examined by EDX. The result shows significant reduction in oxygen percentage after laser cleaning implying the removal of the oxide layer. X-ray photoelectron spectroscopy has been undertaken to determine the surface composition of the as received and laser cleaned surface. The as received surface is dominated by presence of oxygen, carbon with low levels of titanium, nitrogen, silicon, sodium and also with trace amount of calcium and magnesium. Laser processed sample shows considerable reduction in the values of carbon and oxygen and total removal of Si. The amount of nitrogen reduced marginally whereas the quantities of other impurities remain almost unchanged.

2.2.3) Temperature estimation of the laser irradiated surface

Since the dimension of the laser spot (430 µm x 100 µm) is much larger than the thermal diffusion length (0.83 µm), a one dimensional analytical calculation can be carried out to approximate the surface temperature evaluation as function of time and laser intensity. This simple model is based on classical heat conduction equations assuming constant physical properties during irradiation with no convection and no heat generation [14].

The basic heat equation becomes, $$\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad \text{......} \quad (1)$$

At z = 0, surface power density $F_0 = \frac{P(1-R)}{A} = -K\frac{\partial T}{\partial z}$

At $z = \infty$, $\frac{\partial T}{\partial z} = 0$ and at t = 0, $T = T_0$

The solution is,

$$T(z,t) = T_0 + \frac{2F_0}{K}\{\sqrt{\alpha t}\ \mathrm{ierfc}\,[\frac{z}{2\sqrt{\alpha t}}]\} \quad \ldots\ldots(2)$$

Where, $\mathrm{ierfc}(u) = \frac{e^{-u^2}}{\sqrt{\pi}} - u\,[1 - \mathrm{erf}(u)]$

And the error function is defined by $\mathrm{erf}(x) = (\frac{2}{\sqrt{\pi}})\int_0^x \exp(-\zeta^2)\,d\zeta$

Where T (z, t) and T_0 are the temperature at a distance z below the surface at a time t after the initiation of the laser pulse and initial temperature respectively. F_0 is the absorbed intensity on the tube surface, P is the beam power, A is the beam spot area, α is the thermal diffusivity, R is the reflectivity and K is the thermal conductivity of the Ti alloy. If the laser pulse ends at $t = t_p$, then the material will cool for $t > t_p$ according to the following relationship,

$$T(z,t) = T_0 + \frac{2F_0}{K}\sqrt{\alpha t}\ \mathrm{ierfc}\,(\frac{z}{2\sqrt{\alpha t}}) - \frac{2F_0}{K}\sqrt{\alpha(t-t_p)}\ \mathrm{ierfc}\,[\frac{z}{2\sqrt{\alpha(t-t_p)}}] \ldots\ldots\ldots\ldots(3)$$

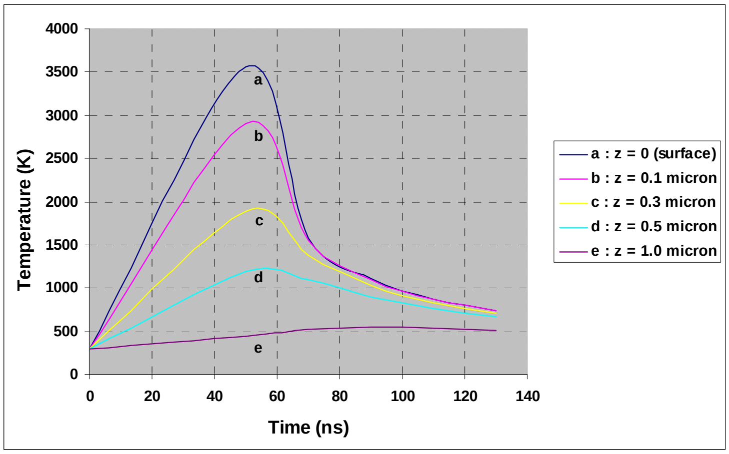
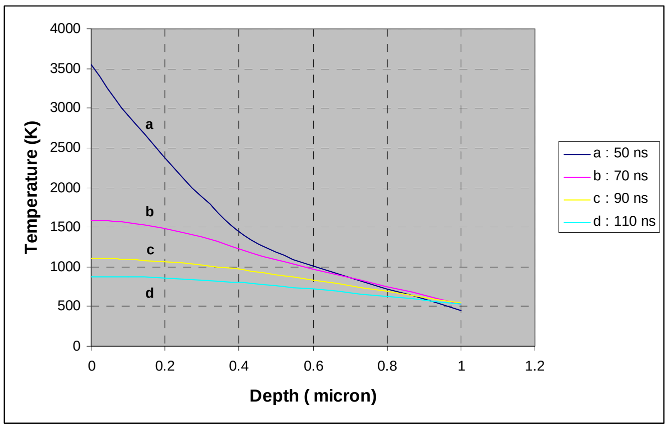


Figure 10: (a) Calculated temperature variation at different depth of the substrate after laser irradiation.

The oxide layer present on the tube surface mainly consists of oxides of titanium with trace quantity of oxides of aluminum and vanadium. The absorptivity of 1064 nm radiation by these constituent oxides is known to be very less.

For temperature calculation the thin oxide layer is assumed to be transparent. Hence the incident laser energy is practically absorbed by the top surface of the tube (z = 0). The process parameters and material properties used for temperature calculation are shown in table 1. Figure 10 a shows the calculated temperature variation at different depth of the substrate after irradiation by the laser pulse. It is seen that the surface temperature increases throughout the laser pulse duration (50 ns) and drops immediately after it ceases. Due to the finite time of heat conduction, temperature at interior locations, below the surface, increases at slightly later time. Figure 10 b shows the estimated temperature at various depth of the irradiated material after different time of the initiation of the laser pulse. It is seen that temperature does not rise over melting point beyond a depth of few tenths of a micron from the surface. Figure 10 c shows the variation in temperature of the top surface at different fluences. Several physical mechanisms are involved in laser cleaning process, depending on the material's properties and laser parameters. The temperature of a thin layer of the material underneath the oxide layer reaches vaporization temperature under the irradiation by the short laser pulse and the layer ablates. The surface oxide layer is removed by the interface pressure developed by ablation. Laser ablation by fast thermal explosion as well as generation of thermo-elastic



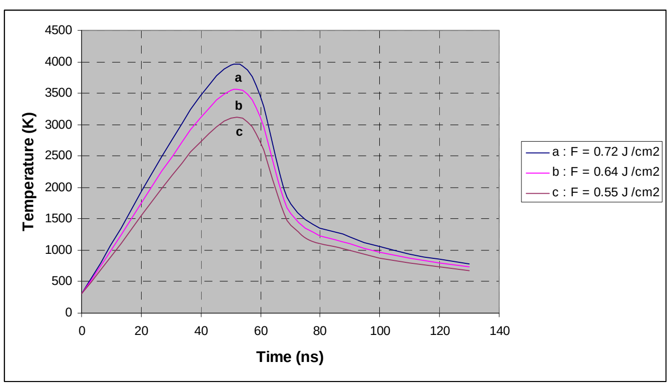


Figure 10(b) Calculated temperature at various depths of the irradiated surface after different time of the initiation of the pulse.
© Variation in temperature of the top surface at different fluences.

Table 1

Parameters used in temperature calculation

Parameters	**Values**
Laser energy/pulse (E)	0.3×10^{-3} J
Spot size (A)	430 µm x 100 µm
Pulse duration (t_p)	50 ns
Thermal Conductivity (K)	8.3 W/m/K
Density (ρ)	4.48×10^{3} Kg/m^3
Specific heat (C_p)	540 J/Kg/K
Absorptivity*	0.44

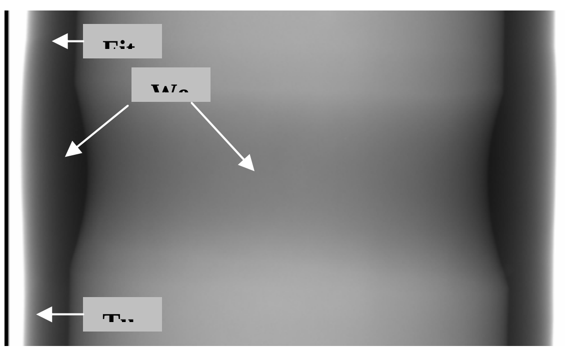
** No data available for Ti-3Al-2.5V, taken the data of Ti from reference 16.*

stresses seem to be responsible for cleaning operation. Some cumulative heating occurs while cleaning, as the pulse repetition rate is high to allow a complete thermal relaxation within the time interval between two consecutive laser pulses. However considering the present application, the rise in temperature does not degrade the material property.

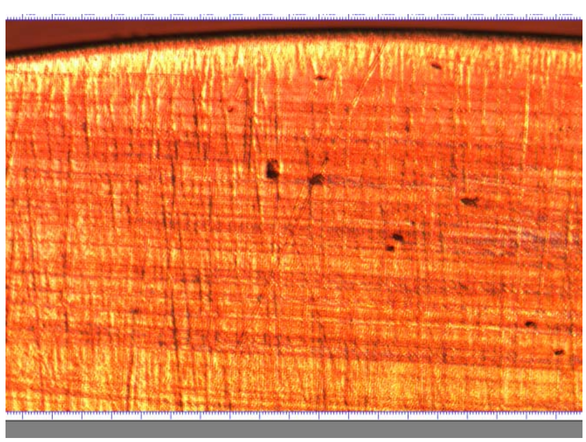
2.3) Welding of laser cleaned tubes with end fittings

After laser cleaning of the edges, the tubes are welded immediately with tube fittings by PGTAW technique. The welding is done inside a small gas purged chamber of an orbital welding machine (LIBURDI make). The fitting is placed properly in the adaptor of the welding chamber and the laser cleaned tube is docked with the end fitting such that the joint is made right in front of the electrode mounted on the rotating head. High purity argon gas is purged in the chamber and also through the inner side of the tube and fitting during welding to protect weld pool, solidified weld and heat affected zones on the face and root side of the weld. A constant current inverter power source (160 A) with high frequency arc starting is used for welding with straight polarity (DCEN). A tungsten 2%

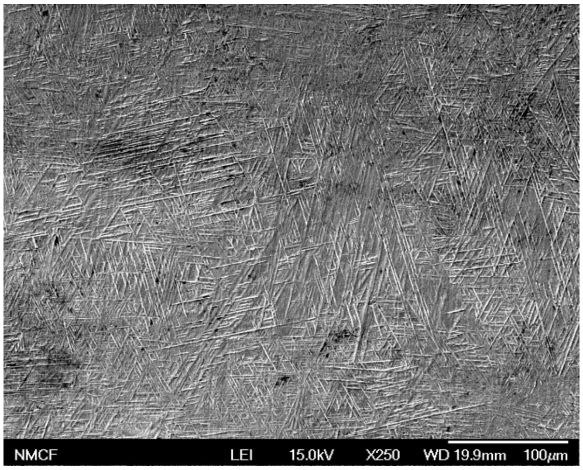
thoriated electrode (diameter 2.4 mm) with included angle ~ 30 degrees is used for the autogeneous welding between the tube and tube fitting. The welding schedule has been programmed with pre purge, post purge of gas for proper shielding and suitable down slope time to extinguish the arc at a lower current value to avoid a crater at the end of the welding. In pulsed mode welding takes place during each peak current period and the molten material cools during the background period. Complete welding along the seam is obtained by proper overlapping of each individual spots, which is decided by the pulse frequency and the weld speed. Table 2 shows the optimized welding parameters. Bright silver colored welds without any atmospheric contamination have been obtained. The welds have been evaluated by radiography (2-2T sensitivity), SEM and metallography. No major defects like porosity, lack of fusion, inclusion, concavity etc. has been obtained. Figure 11(a, b& c) shows the radiograph, photomicrograph and SEM of a weld. Typical basket weave structure in the fusion zone of these alloys is seen in the SEM



(a) Radiograph of a PGTAW weld between tube and tube fitting made with laser cleaned components



(b) Photomicrograph of the cross section of a weld (unetched).



© SEM of the weld metal

Figure :11

Table 2

Welding parameters

Parameters	**Values**
Peak welding current (I_P)	53A
Base welding current (I_B)	7A
Welding speed	6 rpm
Frequency	10 Hz
On time	35 %
Arc gap	0.7 – 0.8 mm
Gas and purity	Argon ,better than 99.996%
Gas flow rate	0.5 lpm

3) **Conclusion**

The surface preparation of Ti-3Al-2.5V tubes using a pulsed fiber laser has been demonstrated. Cleaning threshold and damage threshold parameters have been found out experimentally at different repetition rates. A prototype for cleaning and welding the tubes has been designed, fabricated and installed on a small cart (figure12). The entire process of cleaning and welding takes approximately 20 minutes. Further time reduction is possible with high power lasers. Welds made with laser cleaned tubes are found to be acceptable. The fabricated prototype has been used to clean straight tubes with a length of

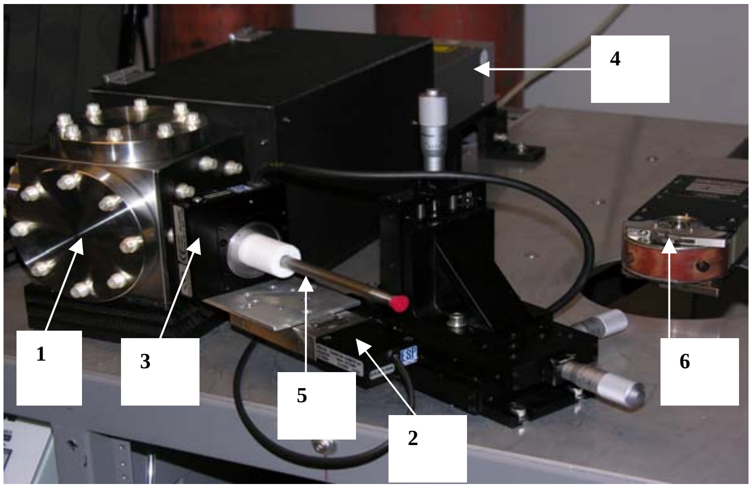


Figure 12: Laser cleaning and welding system on a small cart, 1) SS cleaning chamber,2) X-translational stage, 3) Rotational stage, 4) Fiber laser, 5) Ti alloy tube, 6) Orbital welding head.

few hundreds of millimeters. However, cleaning of very long tubes (several meters) with a bend may pose some difficulty. Designing a system, with stationary tube and rotating beam by a fiber optic delivery probably will be a solution to clean long bend tubes. Cleaning of titanium alloy tubes is very important to the aviation industry. Utilization of this safe and environmentally friendly cleaning technology could have a major advantage in the aviation industry.

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Publications

1.“Surface preparation of Ti-3Al-2.5V alloy tubes for welding using a fiber laser”- Aniruddha Kumar and M. C. Gupta, ***Optics and laser in Engineering***, vol 47, p. 1259 (2009).

2. “A study on laser assisted cleaning and welding of Ti- 3Al-2.5V alloy tubes” **–** Aniruddha Kumar, Mark Sapp, Jay Vincelli and M. C. Gupta, ***Journals of Materials Processing Technology, vol 210, p. 64 (2010).***

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